Analysis of oxy-fuel combustion as an alternative to combustion with air in metal reheating furnaces

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ABSTRACT

Using oxygen instead of air in a burning process is at present being widely discussed as an option to reduce CO_2 emissions. One of the possibilities is to maintain the combustion reaction at the same energy release level as burning with air, which reduces fuel consumption and the emission rates of CO_2. A thermal simulation was made for metal reheating furnaces, which operate at a temperature in the range of 1150—1250 °C, using natural gas with a 5% excess of oxygen, maintaining fixed values for pressure and combustion temperature. The theoretical results show that it is possible to reduce the consumption of fuel, and this reduction depends on the amount of heat that can be recovered during the air pre-heating process. The analysis was further conducted by considering the 2012 costs of natural gas and oxygen in Brazil. The use of oxygen showed to be economically viable for large furnaces that operate with conventional heat recovering systems (those that provide pre-heated air at temperatures near 400 °C).

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1. Introduction

Global warming is mainly caused by fossil fuel combustion and it constitutes today one of the most difficult challenges for humanity to overcome. Fossil fuels provide a significant fraction of the global energy resources, and this is likely to remain so for several decades [1], and a 51% increase in emissions is expected by 2030 [2]. Countries of emerging economies, such as China, today the largest CO_2 emitter in the world, with nearly 10 Gt of CO_2 in 2012 [3], constitute a source of serious concern for the lack of control of these emissions. Thus it is necessary to have new regulations that aim at reducing greenhouse gases, as indicated by the Kyoto protocol. These regulations introduced the perspectives for development of CCS (carbon capture and storage) technologies in the global fight against climate change, such as low-carbon technology which is a vital component to reduce future carbon emissions [4].

The emission of greenhouse gases from energy plants can be reduced by the use of alternative or renewable energy sources. These sources have been gaining ground in the last few years, but until they can generate significant quantities of energy, the present demand must be satisfied by the use of fossil fuels but in systems/manners that use better their heating power and reduce effectively their harmful effects [5].

One of the most promising alternatives is the capturing and storing of the CO_2 in the fossil fuel burning process to avoid its release into the atmosphere. However, this burning process, when done with air, generates CO_2 in low concentrations, making it difficult to capture (the process has a low yield and has high energy requirements). The presence of NO_x and SO_x is also a problem in these processes of carbon capturing [1]. These problems can be overcome using an oxygen-enriched or pure oxygen atmosphere for the combustion process. The enrichment of air with oxygen is an interesting alternative of optimizing the incineration rates in combustion chambers originally conceived for operating with air alone, fixing the combustion temperature, turbulence level and residence times as parameters [6].

Oxy-fuel pressurized combustion of coal and other selected solid fuels has also been investigated. The process was shown to recover more thermal energy from the flue gas because the high pressure raises the dew point and the available latent enthalpy in the flue gases [7]. Also, the NO emission under high pressures was found to be significantly reduced (up to 50%), which was credited to the effect on the char/NO reaction [8].

Oxygen can be used in four primary ways: a) adding into the incoming combustion air stream, b) injecting into an air/fuel flame, c) replacing the combustion air with high-purity O_2, and d) separately providing combustion air and O_2 to the burner [9]. In the third case, the cost of pure oxygen can be justified by the high temperatures reached. The temperature of the flame increases considerably when the air is replaced by oxygen. In a standard

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Nomenclature

$c_{p,Pi}$	specific heat at constant pressure of each of the products (kJ kg^{-1} K^{-1})
$c_{p,Ri}$	specific heat at constant pressure of each of the reactants (kJ kg^{-1} K^{-1})
n_{Pi}	number of moles of each of the component gases of the combustion products
n_{Ri}	number of moles of each one of the reactants
LHV	fuel lower heating value (kJ kg^{-1})
LHV$_c$	lower heating value of combustibles in the combustion products (kJ kg^{-1})
$\dot{m}_{O_2}$	mass flow rate of oxygen (kg s^{-1})
$\dot{m}_t$	mass flow rate of product gas (kg s^{-1})
$\dot{m}_{t1}$	mass flow rate of product gas for combustion with air (kg s^{-1})
$\dot{m}_{t2}$	mass flow rate of product gas for combustion with oxygen (kg s^{-1})
$\dot{m}_1$	mass flow rate of fuel for combustion with air (kg s^{-1})
$\dot{m}_2$	mass flow rate of fuel for combustion with oxygen (kg s^{-1})
$\overline{M}$	flue gas molecular mass (kg kmol^{-1})
$\overline{M}_1$	flue gas molecular mass for combustion with air (kg kmol^{-1})
$\overline{M}_2$	flue gas molecular mass for combustion with oxygen (kg kmol^{-1})
$\dot{n}_t$	molar flow rate of product gas (kmol s^{-1})
$\dot{n}_{t1}$	molar flow rate of product gas for combustion with air (kmol s^{-1})
$\dot{n}_{t2}$	molar flow rate of product gas for combustion with oxygen (kmol s^{-1})
p	pressure (Pa)
$\overline{R}$	universal gas constant (Pa m^3 kmol^{-1} K^{-1})
t_R	residence time (s)
t_{R1}	residence time for operation with air (s)
t_{R2}	residence time for operation with oxygen (s)
T	product gas temperature (K)
T_{ad}	adiabatic flame temperature (K)
T_i	reactants temperature (K)
T_p	reactants pre-heating temperature (K)
V	chamber volume (m^3)
X	recirculation fraction
ΔH_1	difference between enthalpies at adiabatic flame temperature and at the temperature of furnace operation, for operation with air (kJ)
ΔH_2	difference between enthalpies at adiabatic flame temperature and at the temperature of furnace operation, for operation with oxygen (kJ)

burning process with air, more than 70% of the volume of the exhaust gases is nitrogen. However, if the heat is not properly distributed, the intense radiation of the flame in the oxy-fuel process can damage the refractory walls. To get around this problem, part of the exhaust gases is recycled; as the nitrogen is eliminated the recycled gas is rich in CO_2 [10].

The presence of CO_2 in high concentrations in the combustion chamber affects the transmission of heat, the flame ignition and emissions [11]. The high value of the specific heat of CO_2 compared to that of N_2, causes a reduction in the temperature of the gases [12]. Other than affecting the performance of the combustion, recycling also alters the formation of pollutants such as SO_2, NO_x and CO [13]. High temperatures enhance the formation of NO_x, a problem that can be reduced by using pure oxygen as opposed to oxygen-enriched air (without considering the possible presence of nitrogen in the fuel), even when there is a control of flame temperature while CO is converted to CO_2 [14].

The burning process with oxygen instead of air also implies in the reduction of the volume of exhaust gas, which leads to a higher residence time, a critical factor in the reduction of NO_x, which can be reduced by re-dimensioning the combustion chamber. The recycling of gases also contributes to the reduction of NO_x due to the decrease in O_2 concentration in the combustion zone and by the reduction of the temperature [15].

The burning process using pure oxygen has a number of advantages compared to that using air (only 21% of the air is used in the combustion process), for example, the increase of productivity due to the increase of the temperature of the flame, which, in turn, increases the radiation to the chamber. More material can be processed in a system already in place or a new system can by implemented on a smaller scale, an important factor in plants where space is limited, and furthermore this represents a reduction of cost in the manufacturing process.

Additionally, the elimination of N_2 from the burning process causes a decrease in the volume of the exhaust gases allowing for a reduction in the size of the existing ducts. There is also the increase in efficiency of the treatment of these gases as these pollutants are generated in high concentrations making it easier to remove them [9].

There is an increased cost in using pure oxygen. Its economical use can be investigated by computing thermodynamic parameters of the process [16]. This is the objective of this paper, which analyses the substitution of air by oxygen in high temperature equipment, such as metal reheating furnaces that normally operates with natural gas, in temperatures in the range of 1150–1250 °C. First, an energy analysis is conducted for the oxy-fuel process and compared with the conventional process with air in three situations: a) with no air preheating, b) with air preheating by standard heat exchangers (air temperature of approximately 400 °C), and c) with air preheating by high performance heat exchangers (air temperature of approximately 800 °C).

A thermochemical program was used to determine combustion gases equilibrium conditions [17] necessary for the energy analysis. There are computer codes, as the one used here, that solve the set of equilibrium, mass conservation, and energy conservation equations. Systems that contain ions that appear at high temperatures can also be investigated with such codes. Results are given in terms of combustion gas parameters, as final temperature, chemical composition, density, and specific heats, among others, as function of reactants composition, pressure and temperature.

Next, recirculation, residence time and gas radiation are investigated for all case situations. Finally, an economic analysis is conducted, considering the Brazilian scenario and prices. The procedure for the thermo-economic analysis is similar for other furnace operating temperatures, air preheating temperatures, and country scenarios and costs.

2. Energy analysis

The analysis was performed using natural gas for which the composition was assumed to be 89.36% CH_4, 8.03% C_2H_6, 0.85% C_3H_8, 0.48% CO_2, 1.28% N_2, in volumetric basis [18]. Its molecular mass is 17.65 g/mole. Based on the chemical composition, the Lower Heating Value of this natural gas is 850 kJ/mol. The process with pre-heated air and oxygen is described in Fig. 1.

A set of calculations was performed for different recirculation ratios of the exhaust gases, using as reference the results obtained
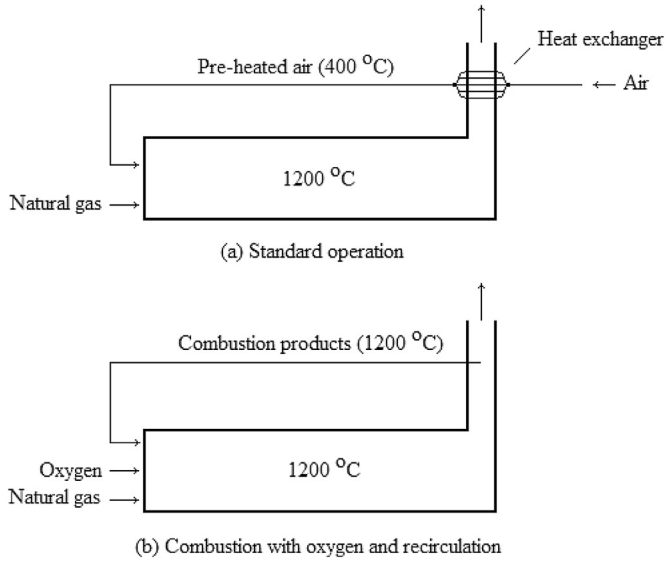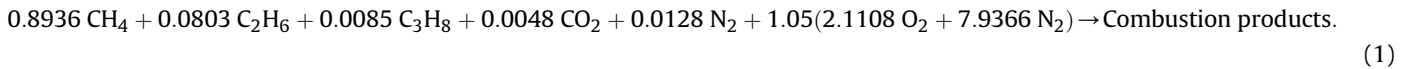
Fig. 1. Scheme of process for standard operation and oxy-fuel combustion with recirculation.

from combustion with pre-heated air at 400 °C. An excess of oxygen of 5% was considered for combustion of natural gas. The global reaction for the combustion of 1 mol of gas with air is:

Fig. 2 presents the product gas enthalpies as functions of temperature and in terms of the percentage of the fuel LHV. For a certain operation temperature (for example, as in the case considered here, 1200 °C), the relation between the mass flow rates of fuel for combustion with oxygen, $\dot{m}_2$, and for combustion with air, $\dot{m}_1$, to provide the same amount of heat in the combustion chamber, is given by:

$$\frac{\dot{m}_2}{\dot{m}_1} = \frac{\Delta H_1}{\Delta H_2}, \qquad (3)$$

where ΔH_2 and ΔH_1 are the differences between the enthalpies at the respective adiabatic flame temperatures and the enthalpies at the temperature of furnace operation.

Fig. 3 presents the ratio between mass flow rates of fuel for combustion with oxygen and with air for different pre-heating temperatures. Pre-heating at 800 °C was included in view of high efficiency ceramic heat exchanging systems that are nowadays in the market. For the standard operation of air pre-heating at 400 °C, the mass flow rate of fuel can be reduced by 28%. This number is even further reduced if the operation temperature is higher than 1200 °C. Oxygen has to be paid for oxy-fuel operation, and its mass flow rate, $\dot{m}_{O_2}$, in terms of the original mass flow rate of fuel, $\dot{m}_1$, is:
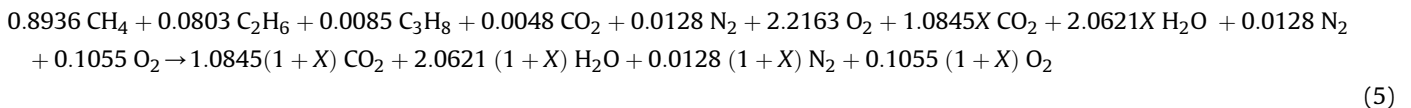
$$\frac{\dot{m}_{O_2}}{\dot{m}_1} = \frac{\dot{m}_{O_2}}{\dot{m}_2}\frac{\dot{m}_2}{\dot{m}_1} = \frac{1.05 \times 2.1108 \times 32}{17.65}\frac{\dot{m}_2}{\dot{m}_1} = 4.02\frac{\dot{m}_2}{\dot{m}_1}. \qquad (4)$$

If a fuel economy is defined as $1 - \dot{m}_2/\dot{m}_1$, it is worth saying that the graph of the oxygen/fuel ratio, $\dot{m}_{O_2}/\dot{m}_1$, as function of the fuel

$$0.8936\,CH_4 + 0.0803\,C_2H_6 + 0.0085\,C_3H_8 + 0.0048\,CO_2 + 0.0128\,N_2 + 1.05(2.1108\,O_2 + 7.9366\,N_2) \rightarrow Combustion\ products. \qquad (1)$$

The combustion reaction with pure oxygen is similar to the above, but with no N_2 from the air. The composition of the combustion products will be given by chemical equilibrium.

The energy balance equation to determine the adiabatic flame temperature is:

$$LHV + \int_{T_i}^{T_p} \left[\sum_i n_{Ri}c_{p,Ri}\right] dT = \int_{T_i}^{T_{ad}} \left[\sum_i n_{Pi}c_{p,Pi}\right] dT + LHV_c, \qquad (2)$$

where LHV is the fuel Lower Heating Value, defined at the reactants temperature T_i (taken as 25 °C = 298 K), n_{Ri} is the number of moles of each one of the reactants (i = natural gas, O_2, and N_2), n_{Pi} is the number of moles of each one of the component gases of the combustion products (i = CO_2, CO, H_2O, H_2, O_2, N_2, etc), $c_{p,Ri}$ is the specific heat at constant pressure of each of the reactants, $c_{p,Pi}$ is the specific heat at constant pressure of each of the products, T_i is the reactants temperature, T_p is the reactants pre-heating temperature, T_{ad} is the adiabatic flame temperature, and LHV_c is the Lower Heating Value of combustible gases that eventually may appear in the combustion products.

economy is a straight line not only for a particular pre-heating temperature, but it is the same straight line for all pre-heating temperatures, as shown in Fig. 4 (only segments are distinct). The operation temperatures on each of the segments range from 1100 °C (upper point on the left) to 1300 °C (lower point on the right). It can be observed that the relative expenditure with oxygen decreases as the furnace operation temperature increases. However, oxy-fuel operation will not be economical when compared to operation with air at high efficiency heat recovery if the cost of oxygen per unit mass is on the order of or higher than the cost of fuel saved during the change.

3. Recirculation

One of the concerns of using pure oxygen in combustion processes is the high maximum temperatures achieved in regions of the furnace. Recirculation lowers the maximum temperature, but does not influence the reduction that can be achieved in fuel consumption. The output of the thermochemical program confirms that the combustion products of natural gas at 1200 °C are CO_2, H_2O, O_2 and N_2. Therefore, the combustion reaction at this temperature, with a recirculation fraction of X can be written as:

$$0.8936\,CH_4 + 0.0803\,C_2H_6 + 0.0085\,C_3H_8 + 0.0048\,CO_2 + 0.0128\,N_2 + 2.2163\,O_2 + 1.0845X\,CO_2 + 2.0621X\,H_2O + 0.0128\,N_2$$
$$+ 0.1055\,O_2 \rightarrow 1.0845(1+X)\,CO_2 + 2.0621\,(1+X)\,H_2O + 0.0128\,(1+X)\,N_2 + 0.1055\,(1+X)\,O_2 \qquad (5)$$
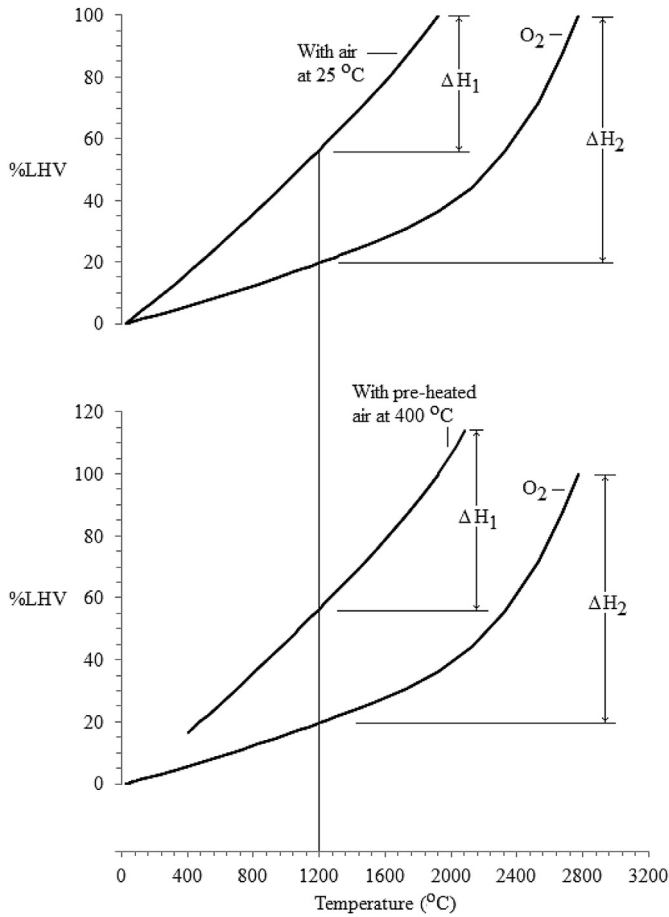
Fig. 2. Product gas enthalpies as functions of temperature.

Fig. 5 presents the maximum chamber temperature, taken as approximately the adiabatic flame temperature, as function of the recirculation fraction. It is observed that the same adiabatic flame temperature for operation with pre-heated air at 400 °C and with oxygen is obtained for a recirculation fraction 2.49. A recirculation fraction of 2.49 means that about 5/7 of the exhaust gas is recycled back, since 2.49/(1 + 2.49) ~ 5/7.

These values of recirculation fraction and corresponding temperatures are located inside the envelope of flameless oxidation [19]. This combustion regime is characterized by uniform temperature distribution and very low emissions of NO_x [20]. Flameless oxidation can be achieved not only in oxy-fuel combustion but also in processes with highly preheated air.
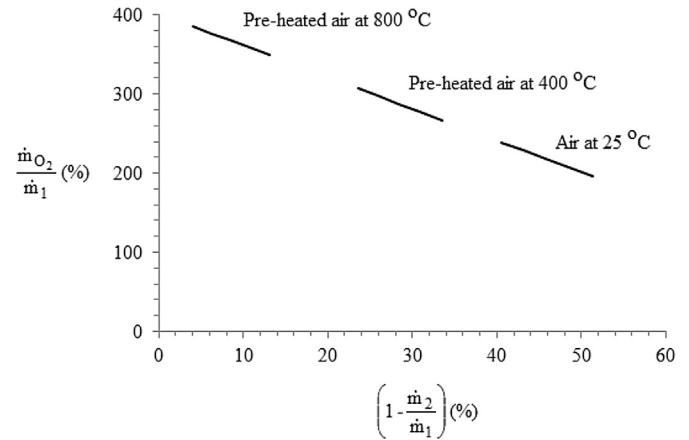

Fig. 4. Mass flow rate of oxygen required as function of the economy on the mass flow rate of fuel.

4. Residence time

The residence time is given by [21]

$$t_R = \frac{pV\overline{M}}{\overline{R}T\dot{m}_t},$$ (6)

where V is the chamber volume, p is the pressure, $\overline{M}$ is the combustion gas molecular mass, $\overline{R}$ is the universal gas constant, T is the combustion gas temperature, and $\dot{m}_t$ is the combustion gas mass flow rate. For operation at the same temperature (obtained with a recirculation fraction X), the ratio between the residence times for operation with oxygen, t_{R2}, and operation with air, t_{R1}, is

$$\frac{t_{R2}}{t_{R1}} = \frac{\overline{M}_2}{\overline{M}_1}\frac{\dot{m}_{t1}}{\dot{m}_{t2}} = \frac{\frac{\dot{m}_{t2}}{\dot{n}_{t2}}}{\frac{\dot{m}_{t1}}{\dot{n}_{t1}}}\frac{\dot{m}_{t1}}{\dot{m}_{t2}} = \frac{\dot{n}_{t1}}{\dot{n}_{t2}},$$ (7)

where $\dot{n}_t$ is the combustion gas mole flow rate. Observing the combustion reaction with recirculation and noting that nitrogen appears in the products for combustion with air, then

$$\frac{t_{R2}}{t_{R1}} = \frac{1.0845 + 2.0621 + 0.0128 + 0.1055 + 2.2163*3.76}{(1+X)(1.0845 + 2.0621 + 0.0128 + 0.1055)}$$
$$= \frac{3.552}{1+X},$$ (8)

which, for $X = 2.49$ produces a relation $t_{R2}/t_{R1} = 1.02$, that is, the residence time remains approximately the same when processes

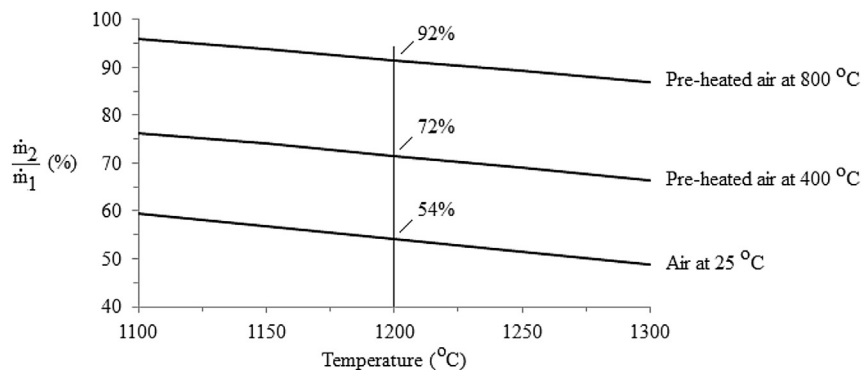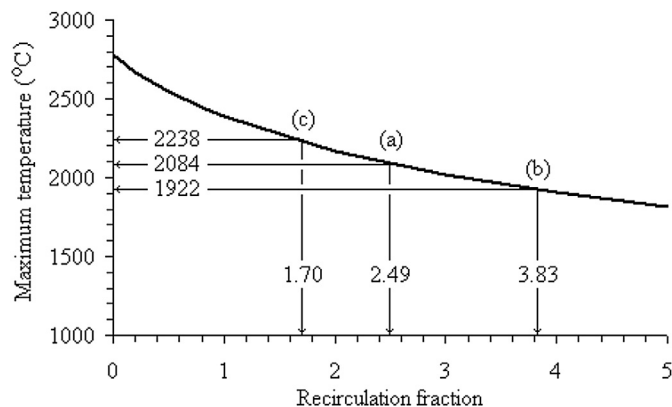Fig. 3. Ratio between mass flow rates of fuel for combustion with oxygen and with air.

Fig. 5. Maximum chamber temperature as function of the recirculation fraction; (a), (b) and (c) correspond to operation with air at 400 °C (standard), 25 °C (no pre-heating), and 800 °C (high efficiency heat recovery), respectively.

with pre-heated air at 400 °C and with oxygen at a recirculation fraction of 2.49 are compared (in this case, the maximum temperature is the same for both processes). On the other hand, $X = 1.70$ produces a relation $t_{R2}/t_{R1} = 1.32$, which means that when a combustion process with pre-heated air at 800 °C is replaced by an oxy-fuel process with same maximum chamber temperature, the residence time increases by 32%. Changes in residence time will be used in conjunction with changes in product gas emissivity, in next item, to estimate the potential of increasing furnace productivity when operating in oxy-fuel conditions.

5. Gas radiation

Radiation heat transfer as a result of the passage of non-sooty gaseous products in a combustion chamber occurs mainly due to water vapor and carbon dioxide [22]. The emissivity of the gas mixture is a function of the partial pressure of its emitting components and of the mean beam length. The mean beam length for a combustion enclosure can estimated by $3.6V/A$, where V is the chamber volume and A is the total enclosure surface area.

For a total pressure of 1 atm, the partial pressures of water vapor and carbon dioxide are: a) $p_{H2O} = 0.178$ atm and $p_{CO2} = 0.094$ atm, for combustion with air, and b) $p_{H2O} = 0.632$ atm and $p_{CO2} = 0.332$ atm, for oxy-fuel combustion. Using the standard procedure to determine gas emissivity [23], the gas emissivity for oxy-fuel combustion and combustion with air was determined as function of the mean beam length, and the result is presented in Fig. 6.
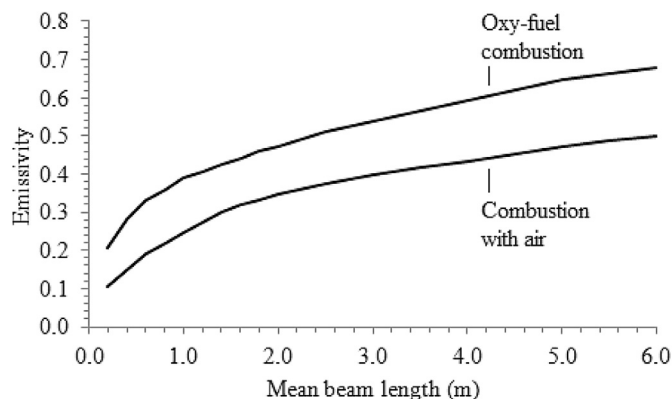
Using the data of Fig. 6, the ratio between the gas emissivity for oxy-fuel combustion and for combustion with air was computed. The results are presented in Fig. 7, which shows that, for mean beam lengths above a certain value, the relation is practically constant. In the case considered here, if the furnace has a square cross section with sides l and a length of 4l, then $l = 2.5$ m corresponds to a mean beam length of 2.0 m.

For a recirculation fraction of 2.49 (comparison of oxy-fuel condition with that of pre-heated air at 400 °C), the relation between the residence times is near 1.00 and the potential for productivity increase is 36%, corresponding to the increase of the emissivity. On the other hand, for a recirculation fraction of 1.70 (comparison of oxy-fuel condition with that of pre-heated air at 800 °C), the relation between residence times is 1.32 and the potential for productivity increase is 80%. This discussion does not consider the effects on the material that will be heated at a faster rate.

6. The Brazilian scenario regarding costs

In Brazil, particularly in the Southeast region, natural gas was introduced at the end of the 1990's by companies that subsidized or financed the acquisition of new combustion equipment by the group of clients that could consume the fuel that was just becoming available in the country. There was no strong concern with the technological level of the products that were introduced in the market; the objective was to obtain short term practical and economical solutions for both parts.

In this context, a large portion of the small size metallurgic furnaces – those with power output up to 4.184×10^6 kJ/h or 1.163 MW – were not equipped with low emission burners or with heat exchangers to pre-heat the combustion air. This led to a scenario of low energy efficiency, with companies which were not efficient in the point of view of the fabrication process chain.

Also, for the large metallurgic furnaces that operated with heavy fuel oil, which already possessed centralized heat exchangers, there was no preoccupation with the installation of new technologies for heat recovery to change the fuel to natural gas. The result was combustion air temperatures that varied between 300 and 350 °C. In general terms, the following is observed regarding air pre-heating temperatures in large metal re-heating furnaces in Brazil today: a) 300–350 °C for equipment originally built for fuel oil and adapted to natural gas, b) 400–450 °C for new equipment designed for natural gas, and c) 600 °C in isolated cases of modern high cost equipment.
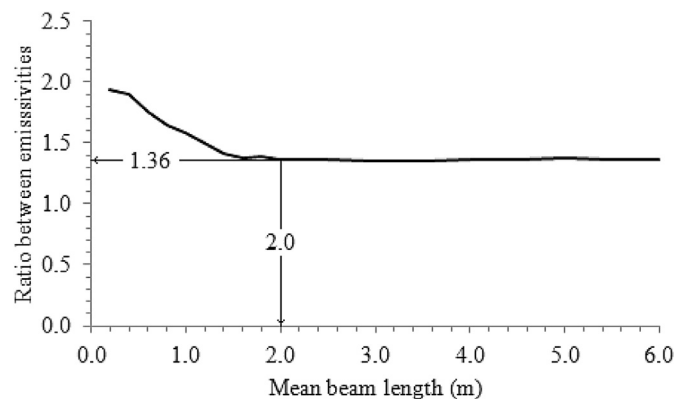

Fig. 6. Gas emissivity for oxy-fuel combustion and combustion with air (chamber average temperature of 1200 °C).

Fig. 7. Ratio between gas emissivity of oxy-fuel combustion and gas emissivity for combustion with air (chamber average temperature of 1200 °C).

With the increasing cost of thermal energy, efficiency has become a very concerning issue for the development of the country.

The following is result of a survey done with companies settled in Brazil and that commercialize natural gas and oxygen.

The price of natural gas (2012) in Brazil varied from US$ 0.54/Nm^3 for large consumers (those above 6,975,000 Nm^3/month) to US$ 0.72/Nm^3 for small consumers (those up to 97,000 Nm^3/month) [24]. The conversion for the Brazilian currency (the real, R$) used here was R$ 2.063/US$, the value on the last week of June 2012.

Regarding the oxygen, several technologies are in the market to separate it from the air, and the most common of them is cryogenic distillation [25]. Besides this process, there are also the membrane technology [26], the PSA(pressure swing adsorption) [27] and the VPSA(vacuum pressure swing adsorption) [28].

The prices of oxygen [29] depend on the demand for the gas. For cryogenic and VPSA plants, the cost of electrical energy is currently (mid 2012) US$ 0.158/kWh. For a capacity of 13,000 Nm^3/h, it is possible to provide oxygen for a combustion installation of up to 65 MW. For this condition and considering that combustion installations usually do not require high pressures for the oxygen, the operational costs, including taxes, are US$ 0.063/Nm^3O_2 for the cryogenic process (0.40 kWh/Nm^3O_2) and US$ 0.058/Nm^3O_2 for the VPSA process (0.40 kWh/Nm^3O_2). For small demands (1250–2500 Nm^3/h), the oxygen will be delivered in bottles or tanks, and the prices are approximately US$ 0.27/Nm^3O_2.

7. Discussion

With reference values for natural gas and oxygen, the economic viability of the use of oxygen can be estimated by inserting the costs in Fig. 4. Fig. 8 presents the expenditure with oxygen as function of the savings obtained by decreasing the consumption of natural gas. As in Fig. 4, the operation temperatures on each of the segments range from 1100 °C (upper point on the left) to 1300 °C (lower point on the right). With the current natural gas and oxygen prices in Brazil, the use of oxygen shows to be economically viable, in terms of current operational costs, for large combustion equipment with conventional heat exchange systems, for chamber temperatures

above 1200 °C. It is also viable for large combustion systems with no heat recovery.

The effect of increases or decreases of natural gas and oxygen prices on the base prices considered in the previous section can be directly evaluated with the data shown in Fig. 8. An increase or decrease of a certain x% on natural gas prices will displace the segments with the same x% to the right or left; an increase or decrease of a certain y% on oxygen prices will raise or lower the segments with the same y%. The straight line represents when the cost of oxygen equals the savings when burning less natural gas. It separates non-competitive substitution from competitive substitution. This line remains the same.

The basic question is about the composition of the natural gas: how does it affect the results of the energy balance? The composition of natural gas in Brazil is different depending on its origin, which can be the Campos coast (Northeast of the state of Rio de Janeiro) or Bolivia. Data for natural gas composition of a major glass manufacturer that receives natural gas from both sources show that LHV varies by up to 6.1% [30].

Gas composition corresponding to maximum and minimum LHVs found in data that is made available on a daily basis from the glass manufacturer were used to evaluate variations in the fuel properties in the analysis. Table 1 shows the composition of the different types of natural gas.

The $\dot{m}_2/\dot{m}_1$ ratio in Eq. (3) and the $\dot{m}_{O_2}/\dot{m}_1$ ratio in Eq. (4) are the main parameters that will be affected by different gas composition. The constant 4.02 in Eq. (4) is different for a different natural gas, but will still be a constant if oxygen is used to replace air with the same natural gas. Therefore, the accuracy value found for $\dot{m}_2/\dot{m}_1$ will be the same for $\dot{m}_{O_2}/\dot{m}_1$.

The whole procedure was repeated for the two other types of natural gas. The same furnace operating temperatures of 1100, 1200, and 1300 °C were used. The $\dot{m}_2/\dot{m}_1$ ratio was calculated for when combustion air was furnished at the same temperatures of 25, 400, and 800 °C. Results of the variation of this parameter for the natural gas used in this study are shown on Table 2. There is a maximum variation of 0.29% in the ratio; this takes place for combustion air supplied at 25 °C. This variation decreases to values lower than 0.1% for air pre-heat temperatures greater than or equal
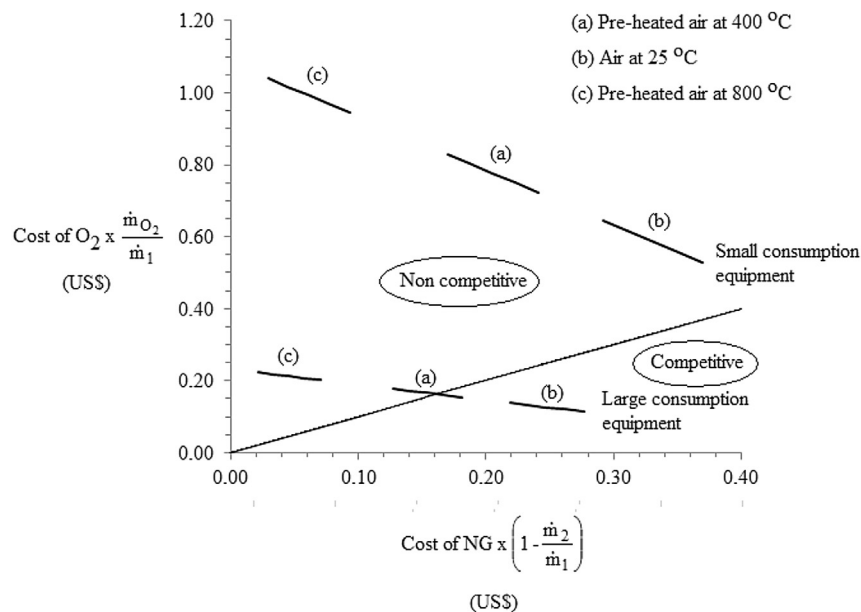

Fig. 8. Expenditure for operation with pure oxygen as function of the savings on the decrease of natural gas consumption.

Table 1
Natural gas composition.

	This study	Max LHV [30]	Min LHV [30]
CH_4 (%)	89.36	88.84	95.62
C_2H_6 (%)	8.03	6.28	2.26
C_3H_8 (%)	0.85	1.78	0.50
C_4H_{10} (%)	–	0.64	0.12
C_5H_{12} (%)	–	0.18	0.03
C_6H_{14} (%)	–	0.08	0.01
CO_2 (%)	0.48	1.63	0.61
N_2 (%)	1.28	0.57	0.86
LHV (kJ/mole)	850	865	815

Table 2
Variation of the $\dot{m}_2/\dot{m}_1$ ratio for the natural gas in this study.

Furnace temperature (°C)		Max LHV	Min LHV
Air temperature: 25 °C			
1100	$\Delta(\dot{m}_2/\dot{m}_1)$	−0.021%	0.16%
1200	$\Delta(\dot{m}_2/\dot{m}_1)$	−0.025%	0.22%
1300	$\Delta(\dot{m}_2/\dot{m}_1)$	−0.030%	0.29%
Air preheat temperature: 400 °C			
1100	$\Delta(\dot{m}_2/\dot{m}_1)$	−0.025%	0.040%
1200	$\Delta(\dot{m}_2/\dot{m}_1)$	−0.028%	0.065%
1300	$\Delta(\dot{m}_2/\dot{m}_1)$	−0.033%	0.096%
Air preheat temperature: 800 °C			
1100	$\Delta(\dot{m}_2/\dot{m}_1)$	−0.035%	−0.038%
1200	$\Delta(\dot{m}_2/\dot{m}_1)$	−0.039%	−0.028%
1300	$\Delta(\dot{m}_2/\dot{m}_1)$	−0.043%	−0.016%

to 400 °C. This indicates that the natural gas formulation used in this study produces general results for the economic analysis, at least for the situation in Brazil.

Finally, the variations in residence time and the partial pressure of water vapor and carbon dioxide for the same operating temperature were also calculated for the two other types of natural gases. They are shown on Table 3. All of these parameters were found to be within 2%.

8. Conclusion

The use of pure oxygen in combustion systems is justified by the economy of fuel and also by the considerable reduction of NO_x emission rates. Chamber productivity can also be improved; based on the increase of product gas emissivity, there is a potential of 36% increase in productivity when using oxygen for the case considered in this article.

For the standard operation of air pre-heating at 400 °C, the mass flow rate of fuel can be reduced by 28% if the chamber temperature is 1200 °C. On the other hand, a price has to be paid for the use of oxygen. Based on Brazilian (mid 2012) natural gas and oxygen prices, oxy-fuel operation is not economical when competing with high efficiency heat recovering systems. It is economical for large combustion units with conventional heat exchange systems for pre-heating the combustion air, for chamber temperatures higher than 1200 °C.

Table 3
Variation of residence time and of partial pressure of water vapor and carbon dioxide in relation to the natural gas in this study.

	Max LHV	Min LHV
$\Delta(t_R)$	1.88%	−0.86%
$\Delta(p_{H2O})$	−0.72%	1.27%
$\Delta(p_{CO2})$	1.68%	−1.26%

The recirculation fraction does not influence the reduction that can be achieved in fuel consumption. Its main objective is to avoid high temperatures that can damage the chamber or affect the industrial process.

Data from a company that uses natural gas from Campos coast and from Bolivia show that the LHV of natural gas in Brazil can vary up to 6.1%. A maximum variation of 0.29% was found in the ratio between the mass flow rate of fuel for combustion with oxygen and the mass flow rate of fuel for combustion with air when using any of the types of natural gas in this study. This indicates that the conclusions on cost savings obtained in this study can be regarded as general for any type of Brazilian natural gas.

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